

Evolution of neutron star + He star binaries: an alternative evolutionary channel to intermediate-mass binary pulsars

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ABSTRACT

It is difficult for intermediate-mass X-ray binaries to form compact intermediate-mass binary pulsars (IMBPs) with a short orbital-period ($\lesssim 3$ d), which have a heavy ($\gtrsim 0.4 M_{\odot}$) CO or ONeMg white dwarf companions. Since neutron star + He star binaries may experience common-envelope evolution, they have some advantage to account for the formation of short orbital-period IMBPs. In this work, we explore the probability of IMBPs formed by this evolutionary channel. Using Eggleton's stellar evolution code, considering that the dead pulsars were spun up by the accreting material and angular momentum from the He star companions, we have calculated the evolution of a large number of neutron star + He star binaries. Our simulated results indicate that, the NS + He star evolutionary channel can produce IMBPs with a WD of $\sim 0.5 - 1.1 M_{\odot}$ and an orbital period of 0.03 – 20 d, in which pulsars have a spin-period of 1.4 – 200 ms. Comparing the calculated results with the observational parameters (spin period and orbital period) of 9 compact IMBPs, the NS + He star evolutionary channel can account for the formation of 4 sources. Therefore, NS + He star binaries offer an alternative evolutionary channel to compact IMBPs.

Key words: stars: formation – binaries: general – stars: neutron – stars: evolution – pulsars: general

1 INTRODUCTION

Millisecond pulsars (MSPs) are characterized by weak surface magnetic fields ($B \sim 10^8$ G), short spin periods ($1 < P_s < 30$ ms), and nearly circular orbits with low-mass ($0.15 M_{\odot} \lesssim M_{\text{wd}} \lesssim 0.4 M_{\odot}$) He white dwarf (WD) companions. These systems are generally called low-mass binary pulsars (LMBPs; e.g. Tauris & van den Heuvel 2006). In contrast to LMBPs, observations found an intermediate-mass binary pulsar (IMBP) population (Camilo et al. 1996, 2001; Edwards & Bailes 2001a), which consists of a pulsar with a spin period of $\sim 10 - 200$ ms and a heavy ($M_{\text{wd}} \gtrsim 0.4 M_{\odot}$) CO or ONeMg WD.

At present, the formation mechanism of LMBPs is well understood. In the standard recycling scenario, LMBPs are the evolutionary products of low-mass X-ray binaries (LMXBs, with hydrogen-rich donor stars of $\lesssim 1.5 M_{\odot}$) via Case A or B Roche-lobe overflow (RLOF) (for a review, see Bhattacharya & van den Heuvel 1991; Verbunt 1993). A pulsar that passed through the so-called death line is spun up to millisecond period by the accretion of material and angular momentum when the donor star fills its Roche-lobe (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982). Meanwhile, mass accretion onto a neutron star (NS) leads

to magnetic field decay (Taam & van den Heuvel 1986; Romani 1990), and the tidal interaction between the NS and the convective envelope of the donor star induces a circular orbit (Phinney 1992; Phinney & Kulkarni 1994). The orbital-periods of LMBPs usually range from 0.2 days to several hundreds days, and are strongly correlated with the WD masses (Tauris & Savonije 1999).

Comparing with the LMBPs, IMBPs have relatively heavy WDs. In addition, the spin periods, the inferred surface magnetic fields, and the orbital eccentricities of the IMBPs are considerably higher than those of the LMBPs (Li 2002). These properties imply that the progenitors and the evolutionary history of IMBPs are distinct from those of LMBPs. It is generally thought that a large fraction of IMBPs are descendants of intermediate-mass X-ray binaries (IMXBs), in which the hydrogen-rich donor stars have a mass in the interval $\sim 1.5 - 10 M_{\odot}$ (van den Heuvel 1975). For example, IMBPs with an orbital-period of 3 – 50 d evolved from IMXBs with a donor star of $\sim 2.5 - 5.0 M_{\odot}$ and an orbital-period of 3 – 10 d via Case B RLOF (Tauris et al. 2000; Podsiadlowski et al. 2002; Tauris et al. 2012). In the IMXB evolutionary stage, the mass transfer rate is much larger than the Eddington accretion rate of the NS. After the rapid mass transfer, the donor star evolves into a low-mass star, and the binary begins LMXB evolutionary phase. The subsequent mass transfer rates are very low, and trigger

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accretion disk instability. The accretion process shows short-lived outbursts separated by long-term quiescence, and the accretion efficiency markedly declines (Li 2002). Although the NS in IMXBs only accretes a transferred amount of material of $\sim 0.01 M_{\odot}$, it can still be spun up to a short spin-period of ~ 10 ms (Tauris et al. 2012).

The IMXBs evolutionary channel successfully explains the majority of IMBPs. However, once the IMXBs evolve into LMXBs phase, the binary orbits should widen because the material is transferred from the less massive secondary to the more massive NS. Therefore, this evolutionary channel cannot produce short orbital-period ($\lesssim 3$ d) IMBPs (Tauris et al. 2000)¹. Nowadays, there exist 18 known IMBPs (their orbital-periods range from 0.4 to 40 d, see also Table 2), in which 9 compact IMBPs have an orbital-period of $\lesssim 3$ d. The origin of compact IMBPs still remains an unresolved puzzle.

The CO WDs in IMBPs can be formed by two evolutionary channels as follows (van den Heuvel 1994): (i) A normal hydrogen-rich star burns helium and hydrogen shells around its degenerate CO core when it is on asymptotic giant branch phase. (ii) A He star with a mass of $\lesssim 2 M_{\odot}$ burns its helium shell (Habets 1986). The former route is an IMXB evolutionary channel, and the latter is a NS + He star evolutionary channel. Most of NS + He star binaries possess a compact orbit (their orbital-periods range from 0.01 to 1.0 d, see also Figure 1 in Chen et al. 2011) because of the common-envelope evolution, and are potential progenitors of compact IMBPs. Recently, Chen et al. (2011) suggested that the progenitor of the short orbital-period IMBP PSR J1802-2124 may be an NS + He star binary with a He star of $1.0 M_{\odot}$ and an orbital-period of 0.5 d. Meanwhile, Tauris et al. (2012) argued that, in post common envelope binaries case BB RLOF of He stars can form most binary millisecond pulsars with CO WD companions. In this work, we attempt to systemically investigate the initial parameter space of NS + He star binaries that could form IMBPs.

2 DESCRIPTION OF BINARY EVOLUTION

2.1 Stellar evolution code

To explore the formation of double NSs binaries, Dewi et al. (2002) and Dewi & Pols (2003) have calculated the evolution of NS + intermediate-mass He star binaries. Similar to their work, we used an updated version of the stellar evolution code developed by Eggleton (1971, 1972, 1973; see also Han et al. 1994; Pols et al. 1995) to calculate the evolutionary sequences of NS (of mass M_{NS}) + He star (of mass M_{He}) binaries, until the systems evolve into the detached binaries. The initial chemical abundance of the He stars was taken to be $Y = 0.98$, $Z = 0.02$, and the ratio of the mixing length to the pressure scale height and the convective overshooting parameter were 2.0, and 0 (Wang et al. 2009), respectively. In addition, the stellar OPAL opacity table originated from a version given by Chen & Tout (2007) (e. g. Rogers & Iglesias 1992; Alexander & Ferguson 1994).

¹ As a possible path, an IMXB can evolve into a compact IMBP by anomalous magnetic braking of Ap/Bp donor star (Justham et al. 2006; Shao & Li 2012).

Table 1. Three evolutionary phases of NSs during mass transfer.

No.	criteria	evolutionary phase	spin evolution
1	$r_{\text{m}} < r_{\text{c}}$	accretion phase	spin-up
2	$r_{\text{m}} > r_{\text{c}}$	propeller phase	spin-down
3	$r_{\text{m}} > r_{\text{lc}}$	radio phase	spin-down

Note: r_{m} , r_{c} , and r_{lc} represent the magnetosphere radius, the co-rotation radius, and the light cylinder radius of the NS, respectively.

2.2 Mass transfer and angular momentum loss

During the evolution of binaries, orbital angular momentum loss play a vital role. In calculation, we consider three types of angular momentum loss from the binary system, which are described as follows:

1. Gravitational wave radiation (GWR). For He star-NS binaries with a compact orbit, GWR can effectively carry away orbital angular momentum and leads to mass transfer. This angular momentum loss rate is

$$\dot{J}_{\text{GR}} = -\frac{32G^{7/2}}{5c^5} \frac{M_{\text{NS}}^2 M_{\text{He}}^2 M^{1/2}}{a^{7/2}}, \quad (1)$$

where G and c are the gravitational constant and the speed of light, respectively; $M = M_{\text{NS}} + M_{\text{He}}$ is the total mass of the binary, and a is the binary separation.

2. Mass loss. During a rapid mass transfer, there may exist mass and angular momentum loss due to the limitation of Eddington accretion rate, in which $\dot{M}_{\text{Edd}} \simeq 3.0 \times 10^{-8} M_{\odot} \text{yr}^{-1}$ for He-rich accretion material. When the mass transfer rate $|\dot{M}_{\text{He}}| > \dot{M}_{\text{Edd}}$, we assumed that the mass loss rate of the system $\dot{M} = \dot{M}_{\text{He}} + \dot{M}_{\text{Edd}}$ proceeds according to isotropic re-emission (Soberman et al. 1997), and carries away the specific orbital angular momentum of the NS. The orbital angular momentum loss rate by the isotropic re-emission is given by

$$\dot{J}_{\text{IR}} = \frac{\dot{M} M_{\text{He}}^2}{M^2} a^2 \Omega, \quad (2)$$

where Ω is the orbital angular velocity of the binary.

3. Magnetic braking. Even if there exist no mass exchange, the coupling between the magnetic field and the stellar winds can also indirectly carry away the orbital angular momentum of binaries (Verbunt & Zwaan 1981). In this work, the induced magnetic braking model given by Sills et al. (2000) was adopted.

2.3 Spin evolution of the NS

In the stellar evolution code, the evolution of the spin and the surface magnetic field of NSs were also considered. In summary, we consider three spin evolution stages in Table 1. The detailed input physics for this subsection see also section 2.3 in Liu & Chen (2011).

3 SIMULATED RESULTS

To explore the initial parameter space of NS + He star binaries that can form IMBPs with various spin-periods, we have calculated the evolution of a large number of NS +

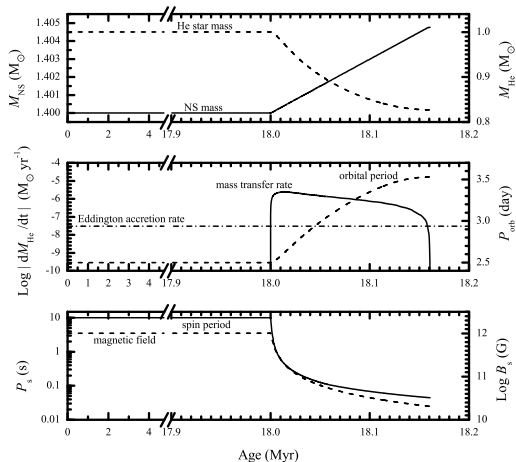


Figure 1. Evolutionary tracks of an NS + He star binary with $M_{\text{He}}^i = 1.0 M_{\odot}$, and $P_{\text{orb}}^i = 2.5$ d. The solid and dashed curves represent the evolution of the NS mass and the He star mass in the top panel, the mass transfer rate and the orbital period in the middle panel, and the spin period and the surface magnetic field of the NS in the bottom panel, respectively.

He star binaries. Employing the population synthesis approach, Chen et al. (2011) found that the initial He star masses and the initial orbital-periods of NS + He star binaries are $M_{\text{He}}^i \sim 0.5 - 2.0 M_{\odot}$, and $P_{\text{orb}}^i \sim 0.01 - 10$ d, respectively. According to their results, we take the simulated grids to be $M_{\text{He}}^i = 0.5 - 2.0 M_{\odot}$, and $P_{\text{orb}}^i = 0.06 - 10.0$ d. For normal radio pulsars, the maximum spin period is 11 s (Manchester 2004), and the final spin periods of NSs is insensitive to the initial spin-periods and the initial magnetic fields (Wang et al. 2011). Therefore, the initial spin-period and the initial magnetic field of the NSs are taken to be 10 s, and 10^{12} G, respectively. Furthermore, a canonical NS mass $M_{\text{NS}}^i = 1.4 M_{\odot}$ was adopted.

In Figure 1, we show the detailed evolutionary sequences of a NS + He star binary with an initial mass $M_{\text{He}}^i = 1.0 M_{\odot}$, and an initial orbital period $P_{\text{orb}}^i = 2.5$ d. After the exhaustion of central He, the He star begins case BB mass transfer at the age of $t \simeq 18.0$ Myr. The rapid transfer of He-rich material occurs at a high rate of $\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$. Because of the Eddington accretion rate, a majority of the transferred material is ejected in the vicinity of the NS, and form the isotropic re-emission. When $t = 18.16$ Myr, the mass transfer ceases, and the binary becomes a detached system. Hereafter, the He star evolves into a CO WD and begins cooling. After mass transfer of 0.16 Myr, the accreted mass for the NS $\Delta M_{\text{NS}} = M_{\text{Edd}} \times 0.16 \text{ Myr} = 0.0048 M_{\odot}$. Though the accreted mass is $\sim 3\%$ of the transferred matter, it is sufficient to spin the NS up to $P_s \approx 45$ ms, and causes the magnetic field to decay to 2×10^{10} G. Owing to the less massive He star transfers the material to the more massive NS, the orbital period continuously increases to 3.53 d.

Figure 2 compiles the final evolutionary fate of NS + He star binaries in the initial He star mass - orbital period ($M_{\text{He}}^i - P_{\text{orb}}^i$) plane. It is seen that NS + He star binaries with He stars of $0.8 - 1.4 M_{\odot}$ can evolve into IMBPs. When the initial orbital period $P_{\text{orb}}^i \leq 0.1$ d, most evolutionary prod-

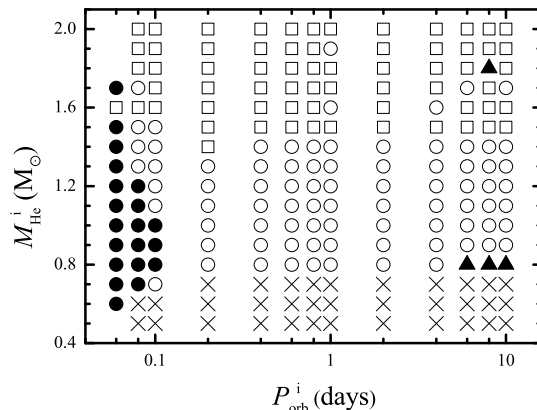


Figure 2. Distribution of the initial He star mass M_{He}^i and the initial orbital period P_{orb}^i of NS + He star binaries that can evolve into IMBPs via the He stars evolutionary channel. The filled circles, open circles, and filled triangles denote IMBPs with spin-period of 1 – 10 ms, 10 – 200 ms, and 200 – 1000 ms, respectively. The open squares correspond to NS + He star binaries that experience dynamically unstable mass transfer, and the crosses represent the binaries in which the He star does not fill its Roche lobe in the Hubble time.

ucts are IMBPs with a millisecond period. If $P_{\text{orb}}^i > 0.1$ d, nearly all NSs are only mildly recycled, and their spin-period are in the range of 10 -200 ms. In particular, in our calculated grids, there exist 4 NS + He star binaries that produce slow spin pulsars with a spin period of 200 – 1000 ms. When the mass ratio of binaries $q = M_{\text{He}}/M_{\text{NS}} > 1$, the envelopes of the He stars is dominated by convection at the onset of RLOF (van den Heuvel 2009). Therefore, a runaway mass transfer is triggered, and nearly all NS + He star binaries with $q > 1$ would experience CE evolution. However, for H main sequence companions in LMXBs or IMXBs with radiative (or only slightly convective) envelopes, and the mass transfer is stable, and can avoid CE evolutionary stage even if $q > 1$ (see also Tauris & Savonije 1999; Tauris et al. 2000; Podsiadlowski et al. 2002; Liu & Chen 2011; Shao & Li 2012).

In order to study how the accreted mass influences the spin evolution of NSs, in Figure 3 we plot the evolutionary results in the accreted mass vs. the final spin period of NSs ($\Delta M_{\text{NS}} - P_s$) diagram. It is clear that, if NSs accrete He-rich material of $\gtrsim 0.02 M_{\odot}$, they will be spun up to millisecond period, and evolve into IMBPs like PSR J1614-2230 (Demorest et al. 2010). As shown in this figure, there exist a practically linear logarithmic inverse correlation between the final spin-period and the accreted mass of NSs, which originates from our model assumption for the spin-up of NSs (see equation 9 in Liu & Chen 2011).

In Figure 4, we present the distribution of our simulated results in the $P_{\text{orb},f} - P_s$ diagram. One can see that our NS + He star evolutionary channel can form IMBPs with an orbital period of 0.03 - 20 d and a spin-period of 1.4 – 1000 ms. It is difficult for our evolutionary scenario to produce IMBPs with a relatively long orbital-period ($\gtrsim 20$ d), which should be derived from the selection of the distribution of the initial orbital-periods. In Table 2, we list the observed

Table 2. Observed parameters for 18 IMBPs.

Pulsars	P_s (ms)	P_{orb} (days)	References
J1420–5625	40.3	34.1	1
J1810–2005	32.8	15.01	2
J1904+0412	71.1	14.93	2
J1454–5846	45.2	12.42	2
J1614–2230	3.15	8.69	3,4
J0621+1002	28.9	8.319	5,6
J1022+1001	16.5	7.805	6
J2145–0750	16.1	6.839	7
J1603–7202	14.8	6.309	8
J1157–5112	43.6	3.507	9
J1528–3146	60.8	3.18	10
J1439–5501	28.6	2.12	11,12
J1232–6501	88.3	1.86	2,13
J1435–6100	9.35	1.35	2,13
B0655+64	195.7	1.03	14,15
J1802–2124	12.6	0.699	11,16
J1757–5322	8.87	0.453	17
J1952+2630 ^c	20.7	0.392	18

References. (1)Hobbs et al. (2004); (2)Camilo et al. (2001); (3)Crawford et al. (2006); (4)Demorest et al. (2010); (5)Splaver et al. (2002); (6)Camilo et al. (1996); (7)Bailes et al. (1994); (8)Lorimer et al. (1996); (9)Edwards & Bailes (2001a); (10)Jacoby et al. (2007); (11)Faulkner et al. (2004); (12)Lorimer et al. (2006); (13)Manchester et al. (2001); (14)Jones & Lyne (1988); (15)Lorimer et al. (1995); (16)Ferdman et al. (2010); (17)Edwards & Bailes (2001b); (18)Knispel et al. (2011) .

parameters for 18 IMBPs. To compare with observations, we also show the locations of 18 IMBPs by the filled stars in Figure 4. As shown in this figure, our calculated results can roughly fit 5 - 6 observed sources. Other sources have much shorter spin period than that predicted by the model. However, for 9 short orbital-period IMBPs, our evolution results can fit 4 sources, suggesting that the NS + He star evolutionary channel may be an interesting evolutionary path to short orbital-period IMBPs.

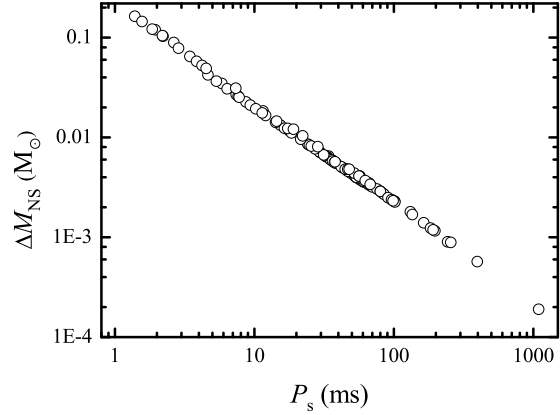
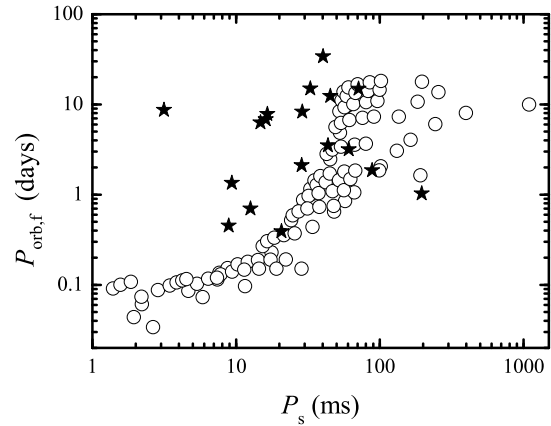
4 DISCUSSION AND SUMMARY

In this paper, we attempt to investigate if IMBPs can have evolved from NS + He star evolutionary channel. We have performed numerical calculations for the evolution of NS + He star binaries consisting of a $1.4 M_{\odot}$ NS and a $0.5 - 2.0 M_{\odot}$ He star companion. Our main results can be summarized as follows.

1. When the He star mass is in the range of $0.8 - 1.4 M_{\odot}$, NS + He star binaries can evolve into IMBPs. If the initial orbital period P_{orb}^i is too short (< 0.1 d), the NS will be fully recycled, and can be spun up to < 10 ms. In other cases, a mildly recycled pulsar with a spin-period of 10 -1000 ms would be produced.

2. During the mass exchange, the accreted mass of most NSs is in the range of $0.001 - 0.18 M_{\odot}$, which is sufficient to spin up the NS to a period of 1 – 200 ms. An accreted mass of $0.02 M_{\odot}$ is the threshold that the NSs are recycled to be millisecond period.

3. The NS + He star evolutionary channel can pro-

**Figure 3.** Distribution of our simulated results in the accreted mass of NSs vs. the final spin-period ($\Delta M_{\text{NS}} - P_s$) diagram.**Figure 4.** Distribution of our simulated IMBPs in the final orbital periods vs. the spin-period of NSs ($P_{\text{orb},f} - P_s$) diagram. The solid stars represent the observed sources.

duce IMBPs with an orbital-period of $0.03 - 20$ d. Out of 9 known short orbital-period IMBPs, our model can address the formation of 4 compact sources. Comparing with the IMXBs evolutionary channel, the NS + He star binaries can form short orbital-period ($\lesssim 3$ d) IMBPs without invoking anomalous magnetic braking of Ap/Bp stars (Justham et al. 2006; Shao & Li 2012).

4. Comparing with the observations, our simulated IMBPs tend to have a long spin-period, or a short orbital-period. There may be three possibilities to explain the difference between observations and our model predictions. Firstly, the NS + He star evolutionary channel only produces a part of observed IMBPs, and the remainder descended from IMXBs (Tauris et al. 2000; Shao & Li 2012). Secondly, the theoretical model of magnetic braking needs to be revised, or super-Eddington accretion of NSs may occur (Begelman 2002). Thirdly, in our calculation we take a canonical NS mass (of mass $1.4 M_{\odot}$), while the NS masses may have a large range of values. Actually, the initial parameter space (especially initial orbital-period) for forming IMBPs in $P_{\text{orb}}^i - M_{\text{He}}^i$ diagram increases with the in-

crease of the NS mass (Shao & Li 2012). Observational and theoretical studies indicate that NSs formed by iron-core collapse supernovae and electron-capture supernovae have obviously different initial mass (see also Nomoto 1984; Timmes et al. 1996; Heger et al. 2003; Woosley & Janka 2005; Schwab et al. 2010; Zhang et al. 2011; Özel et al. 2012). For example, millisecond pulsar PSR J1614- 2230 with a mass of $2.0 M_{\odot}$ was proposed to be originated from IMXB with a massive NS of $1.6 - 1.7 M_{\odot}$ (Lin et al. 2011; Tauris, Langer & Kramer 2011).

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